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HYPERVELOCITY TUNNEL 9 MACH 8 CALIBRATION

BY NANCY F. SWINFORD

STRATEGIC AND SPACE SYSTEMS DEPARTMENT

10 MARCH 1994

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Naval Surface Warfare Center
DAHLGREN DIVISION

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FOREWORD

This report documents the Mach 8 Calibration test program (WTR 1614) performed in the Navy's Hypervelocity Wind Tunnel (Tunnel 9). This was an in-house calibration test entry and the primary objective was to explore the Tunnel 9 Mach 8, low Reynolds number regime. This would supplement previous calibrations of the free stream conditions at Mach 8, high Reynolds number.

The author would like to extend thanks to Mark Kammeyer, Daniel E. Marren, and John F. Lafferty for their comments and suggestions concerning this report.

Approved by:

R. L. SCHMIDT, Head
Strategic and Space Systems Department

ABSTRACT

This report documents the Mach 8 Calibration test program (WTR 1614) performed in the Navy's Hypervelocity Wind Tunnel (Tunnel 9). This was an in-house calibration test effort. Free stream flow field measurements were obtained for the Mach 8 nozzle, covering a wide range of Reynolds numbers. The calibration included running very low Reynolds numbers, not previously calibrated at Mach 8, as well as running at the current maximum supply conditions for Mach 8. The test period was 18 to 23 December 1992, with a total of five runs. Results from this test entry were combined with previous Mach 8 calibration data in the final analysis. Previous calibration data were taken when Mach 8 was originally brought on-line in December of 1988. The maximum supply conditions were lower during the original calibration than are currently available. However, data from this most recent calibration reveal that high quality uniform flow still exists and that deviations in core flow field parameters are comparable with other Tunnel 9 calibration data taken to date.

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INTRODUCTION

Calibration of wind tunnel facilities is necessary to properly evaluate and understand the data obtained during a test program. The Navy's Hypervelocity Wind Tunnel (Tunnel 9) frequently engages in facility calibrations.

When the Mach 8 capability of Tunnel 9 was originally brought on-line in December 1988 (WTR 1474), a characterization of the flow was completed.[1] At that time, Mach 8 calibration data included running only the maximum available supply conditions and Reynolds numbers. At a later time, two additional calibration runs (WTR 1606) were scheduled in between test programs. This was done in an effort to expand the Mach 8 calibration data bank. Since then, upgrades to the facility have allowed higher supply pressures and temperatures to be obtained, as well as improved regulation of these supply conditions.

The present calibration test (WTR 1614) was designed to calibrate the uniformity of the flow field parameters in the Mach 8 nozzle at the current capabilities. It covered a wide range of supply conditions, Reynolds numbers, and usable run times. This effort was combined with previous Mach 8 tunnel calibrations (WTRs 1474 and 1606) to create this comprehensive calibration report.

TEST FACILITY

Tunnel 9 is a blow-down facility which currently operates at Mach numbers of 8, 10, and 14. Ranges for Reynolds numbers and current supply conditions are listed in Table 1.

A general schematic of Tunnel 9 is shown in Figure 1. Mach 8 operates as an open-jet facility, whereas Mach 10 and 14 operate as a closed-jet facility. The Mach 8 nozzle and test cell occupy the space occupied by the nozzle alone in Mach 10 or 14 operation, as illustrated in Figure 2. The Mach 8 nozzle has an exit diameter of 33 inches which exhausts into a 60-inch diameter test cell. This configuration enables testing of large-scale models. The Mach 8 model support system is designed for fixed angle of attack operation but allows model angle of attack to be changed between runs.

Tunnel 9 uses nitrogen as the working fluid. During a typical run, a vertical heating vessel is used to pressurize and heat a fixed volume of nitrogen to a predetermined pressure and temperature. The test cell and vacuum sphere are evacuated to a low pressure and are separated from the heater by a pair of metal diaphragms. When the nitrogen in the heater reaches the desired temperature and

pressure, the diaphragms are ruptured and the gas flows from the top of the heater, expanding through the contoured nozzle into the test cell at the desired test conditions. As the hot gas exits the top of the heater, cooler nitrogen (~300°F) from three pressurized driver vessels enters the heater base. The cold gas drives the hot gas in a piston-like fashion, thereby maintaining constant conditions in the test cell during the run. More detailed information concerning the facility can be obtained from Reference 2.

TEST HARDWARE

Calibration hardware for this test consisted of a 21-probe cruciform Pitot rake mounted on a straight sting and a single independent strut-mounted Pitot. Both were positioned such that the tips of all Pitot probes were located in the first window station, approximately 11 inches downstream of the nozzle exit plane. The cruciform Pitot rake is shown in Figure 3, relative to the Mach 8 test cell windows.

The 21-finger cruciform Pitot rake measured 30.5 inches in width both horizontally and vertically. There were five probes on each arm and one in the center. The probes were situated 3 inches on center, except for the last probe on each arm, which was 2.5 inches on center. The rake was oriented at a roll angle of 26.5° counterclockwise from the vertical plane, looking downstream. A single, strut-mounted Pitot probe was also installed in the Mach 8 test cell. The strut was mounted so that it protruded normal to the test cell wall and was oriented at an angle of 18.5° clockwise from the vertical plane, looking downstream. It supported a single Pitot probe, located 8 inches radially from the centerline of the test cell (22 inches from the test cell wall), halfway between two of the cruciform arms. A schematic of both the cruciform rake and the strut-mounted probe is shown in Figure 4.

INSTRUMENTATION

TUNNEL INSTRUMENTATION

The instrumentation used to monitor wind tunnel supply conditions included one supply pressure (P_0) transducer, two supply temperature (T_0) thermocouples, and the strut-mounted Pitot pressure transducer. The range of the supply pressure transducer was chosen based on the anticipated pressure for each run. The strut-mounted Pitot was instrumented with a 0 to 200 psia XT-140-200A Kulite pressure transducer for all runs. Table 2 lists the pressure instrumentation and the valid ranges. Reference 3 provides more detail on Kulite pressure transducers. For all runs, the supply temperature was measured using Type K chromel/alumel thermocouples with a useful range of 0 to 2000°F. These thermocouples were fabricated in-house.

The strut-mounted Pitot pressure transducer was connected to the Pitot tube using Tygon flexible tubing. Tubing length was sized to minimize the pressure lag, as outlined in Reference 2.

PITOT RAKE INSTRUMENTATION

The cruciform Pitot rake was instrumented with twenty-one 0 to 200 psia XT-140-200A pressure transducers. These transducers were used for all runs, as listed in Table 2.

All cruciform rake pressure transducers were mounted inside the rake. The interior ends of the Pitot tubes were threaded and the pressure transducers were screwed directly into the tubes. With this direct connection, lag problems were eliminated.

CALIBRATION AND TEST PROCEDURES

PRESSURE TRANSDUCER CALIBRATION

Calibration of the pressure instrumentation was accomplished prior to each wind tunnel run. The data system recorded transducer response during evacuation of the test cell. The test cell evacuation was accomplished in steps where the test cell pressure was held constant at each step. For this program, seven calibration points were obtained from atmospheric pressure to approximately 1 mm Hg. Two MKS Baratron type 145 transducers with ranges of 0 to 1000 and 0 to 10 mm Hg were used as comparison standards for the calibration. For each transducer, output voltage was recorded and a slope and intercept were calculated using a least squares method.

RUN SETUP AND INITIATION

After the pressure transducer calibration, preheat static tares were obtained on all transducers. The Mach 8 heating cycle, approximately 10 minutes in duration, was then started. A final tare was obtained at the end of the heating cycle for final instrumentation intercept corrections just prior to diaphragm rupture. Once flow was established, the data acquisition system, photographic coverage, and other tunnel control systems were triggered by the control system event sequencer.

The Mach 8 test cell capabilities include orienting the model at a fixed angle of attack for each run. During this calibration, the cruciform rake was held at a zero degree angle of attack.

DATA ACQUISITION AND REDUCTION

DATA ACQUISITION

Data were sampled and recorded using the Data Acquisition and Recording Equipment (DARE) VI. DARE VI is a simultaneous-sample-and-hold,

single-amplifier per channel system with ±14 bit resolution. The input signals from all DARE channels were amplified and fed through six-pole, low-pass Bessel filters with a cutoff frequency of 25 Hz, thus eliminating high frequency background noise. Each channel sampled data at 250 samples per second. Reference 2 gives a full description of the DARE VI system.

Data taken using the DARE VI were post-processed by applying a software representation of a sixth-order, low-pass Butterworth filter. This type of digital filtering allowed the data to be refined after recording. Time delays in the digital filtering were avoided by filtering the data twice and reversing the data in time between the two applications of the filter. A more complete description of filtering techniques can be found in Reference 2. A cutoff frequency of 10 Hz was used for tunnel supply conditions, the strut-mounted Pitot, and all calibration rake Pitots.

REDUCTION OF FLOW FIELD PROPERTIES

Tunnel supply conditions and test cell pressure measurements were obtained using DARE VI for each wind tunnel run. The data tape for each run was written and, subsequently, reduced on a VAX 4000 computer system.

Data from the P_0 transducer, T_0 thermocouples, strut-mounted Pitot pressure transducer, and cruciform rake Pitot pressure transducers were used to compute local flow field parameters based on an assumption of thermodynamic equilibrium in the inviscid core flow.[4] Real gas effects, referring to the thermodynamic state where intermolecular or Van der Waal's forces are significant, were accounted for by computing an equivalent perfect gas supply pressure and temperature as outlined in Reference 5.

The flow field properties at each Pitot position on the rake were calculated using the data from P_0, T_0, and the corresponding Pitot probe. The free stream properties for the strut-mounted Pitot were calculated in the same manner. The flow field properties at each position on the rake were then normalized by the strut-mounted free stream properties. The T_0 thermocouples were averaged when both were believed to be reliable.

MEASUREMENT UNCERTAINTY

An estimate of the uncertainty of the measured and derived flow quantities is specified in Reference 6. These results are listed in Table 3. The measured quantities were combined with the corresponding uncertainties and are noted on all appropriate figures in this text. The uncertainty for the Pitot pressure measurements was ±0.3 percent in pressure.

RESULTS

DURATION OF USABLE RUN TIME

When the appropriate supply conditions were achieved, the diaphragms were burst and a start-up period followed where the supply pressure and temperature were ramped to prearranged values. Control valves regulated the flow of hot nitrogen from the heater vessel, which produced relatively constant Reynolds number conditions over the total usable run time. For a more complete description of Tunnel 9 operation consult Reference 2.

The usable run time was defined as the length of time during the run where the supply conditions, and consequently the Reynolds number, were held nearly constant. Figure 5 shows a plot of supply conditions and the corresponding Reynolds number versus time for a standard tunnel run. Usable run times varied inversely with supply pressure and Reynolds number and ranged from 200 ms to 750 ms. Table 4 lists the Mach 8 supply and test cell conditions and the coinciding usable run times investigated during this calibration test.

TEMPORAL UNIFORMITY

To evaluate the temporal uniformity, normalized Pitot pressure profiles were plotted at various instants in time during a tunnel run. Each rake Pitot pressure was normalized by the strut-mounted Pitot pressure. Figure 6 shows three normalized Pitot pressure profiles for a typical run at various times during the usable run time. As shown, the profiles vary little with time. The temporal deviations were on the order of 2.6 percent or less in normalized pressure. Based on these observations, the Pitot pressure profiles for each run were averaged over the usable run time.

INVISCID CORE SIZE

The Mach 8 inviscid core size was determined qualitatively for each run based on the character of the normalized Pitot pressure profile, both radially and axially. The rake Pitot pressures were normalized by the strut-mounted Pitot pressure for each run. Since this calibration did not include varying the axial location of the cruciform rake, the determination of the axial variation of the inviscid core size was based on data from previous calibration runs (WTR 1474).

Figure 7 shows the normalized Pitot pressure profile for each run. The radial inviscid core size 11 inches downstream of the nozzle exit was shown to be at least 24 inches in diameter for all supply conditions investigated during this calibration test. The inviscid core may have been larger than the measured 24 inches; however, the actual size was impossible to determine because of the sparse resolution of the Pitot probes on the cruciform rake.

Axially, the inviscid core size was expected to be defined by Mach lines emanating from a point within the boundary layer at the nozzle exit. The flow survey data from WTR 1474 indicated, however, that the diameter of the inviscid core boundary did not decrease as rapidly downstream of the nozzle exit as it would if it followed these Mach lines. The Mach 8 flow survey data indicated inviscid core

diameters of approximately 24, 22, and 20 inches at distances of 5.5, 29.25, and 53.5 inches from the nozzle exit, respectively, at free stream Reynolds numbers of roughly 50 million per foot.[1] However, the inviscid core should conservatively be estimated by the Mach lines. Reference 1 gives extensive information on the details of the WTR 1474 calibration. Figure 8 depicts the axial variation of the inviscid core size for Mach 8.

RADIAL SYMMETRY

The orthogonal structure of the cruciform Pitot rake allowed verification of the radial symmetry of the flow field parameters in the test cell. Only those Pitots that fell inside the inviscid core were used in analyzing the radial symmetry. All rake Pitot pressures were normalized by the strut-mounted Pitot pressure. Figure 9 shows how the normalized Pitot data from all four arms collapse onto a common line when plotted as a function of absolute distance from the test cell centerline. The axisymmetric deviation was 2.2 percent or less in normalized pressure.

RUN REPEATABILITY

During this calibration, run conditions were not repeated. The goal of this Mach 8 calibration was to investigate many different run conditions ranging from very low Reynolds numbers to the maximum attainable Reynolds numbers. Therefore, in order to verify run repeatability, normalized Pitot profiles from this calibration (WTR 1614) were compared to normalized Pitot profiles from previous calibration runs (WTRs 1474 and 1606). For WTR 1614, each rake Pitot pressure was normalized by the strut-mounted Pitot pressure. For WTRs 1474 and 1606, no strut-mounted Pitot was available. Instead, a Pitot was chosen on each arm of the cruciform rake that was approximately the same distance from the test cell centerline as the strut-mounted Pitot in WTR 1614. These four Pitot pressures were averaged to get a free stream Pitot pressure. This average free stream Pitot pressure was then used to normalize the flow field Pitot pressures.

It was desirable to compare runs that were made at the same supply conditions, free stream Reynolds numbers, and axial position in the test cell. However, because of the different goals of WTRs 1474, 1606, and 1614, this was not possible. Therefore, the most similar run conditions were compared in order to evaluate run repeatability. Figure 10 shows a normalized Pitot pressure plot of three separate Mach 8 runs at the most similar supply conditions, free stream Reynolds numbers, and axial position. The characteristic profiles are very repeatable from run to run with a maximum deviation of 4.4 percent in normalized pressure.

PRESENTATION OF RESULTS

Table 5 represents the data from the runs made during this Mach 8 calibration. All data were obtained at one axial station in the test cell, 11 inches downstream of the nozzle exit plane.

The results from the cruciform Pitot rake are presented for each test condition in Appendix A where tabulated flow field parameters verses radial distance from the test cell centerline are listed. Data from both the horizontal and the vertical arms of the cruciform Pitot rake are presented. The flow field Pitot pressure at each probe on

the cruciform rake is normalized by the measured value of the free stream strut-mounted Pitot averaged over the usable run time (PTAVG). All other parameters in Appendix A are normalized in the same manner.

Figures 11 through 18 show the inviscid core flow field data corresponding to Appendix A. The horizontal and vertical profiles, averaged over the usable run time, represents each run condition. This is justified based on the temporal uniformity. These figures are included in this report for pretest planning purposes of future test programs.

COMBINING CALIBRATION RESULTS WITH TEST DATA

The ultimate purpose for the generation of this data is to aid in the definition of the flow field profile during a test program. When a model is tested aerodynamically in Tunnel 9, the Pitot calibration rake will not be installed in the test cell. Flow field conditions are calculated as described earlier based on P_0, T_0, and the strut-mounted Pitot pressure (PTAVG). Refer to Figure 4 for test cell arrangement.

The calibration data can provide a better definition of the flow field profile. To use the calibration data in conjunction with the aerodynamic test data in the final printout, the following procedure exists. The wind tunnel data package will contain the supply conditions and free stream parameters for each run. The free stream parameters are calculated based on the measured supply conditions and the value of the strut-mounted Pitot pressure (PTAVG). The free stream parameters represent the entire flow field across the test cell. This approach assumes constant conditions across the test cell. A profile of each flow field parameter can be inferred, from Appendix A, as a fraction of the PTAVG quantity for each run condition. For completeness, this data should be combined with the measurement uncertainty data from Table 3.

SUMMARY

This Mach 8 calibration test (WTR 1614) covered a wide range of supply conditions, Reynolds numbers, and usable run times. It was prepared with previous Mach 8 tunnel calibrations (WTRs 1474 and 1606) to create this comprehensive report. Usable run times were observed ranging from 750 ms to 200 ms, with corresponding Reynolds numbers ranging from 8.7×10^6/ft to 55.7×10^6/ft. Temporal deviations were on the order of 2.6 percent or less in normalized pressure and the inviscid core diameter 11 inches downstream of the nozzle exit was 24 inches for all supply conditions. The radial symmetry of the Mach 8 free stream flow field showed a 2.2 percent or less deviation in normalized pressure. Run repeatability, for runs compared at similar supply conditions, revealed a 4.4 percent or less deviation in normalized pressure. Based on the various Pitot pressure readings and uncertainties, uniformity in Mach number was determined to be +1.2 percent to -0.7 percent or less.

Overall, the calibration data obtained in the Hypervelocity Tunnel 9 verify that high quality, uniform flow exists at Mach 8. A large inviscid core diameter, combined with a wide range of Reynolds numbers and run times, provides for an excellent Mach 8 test environment.

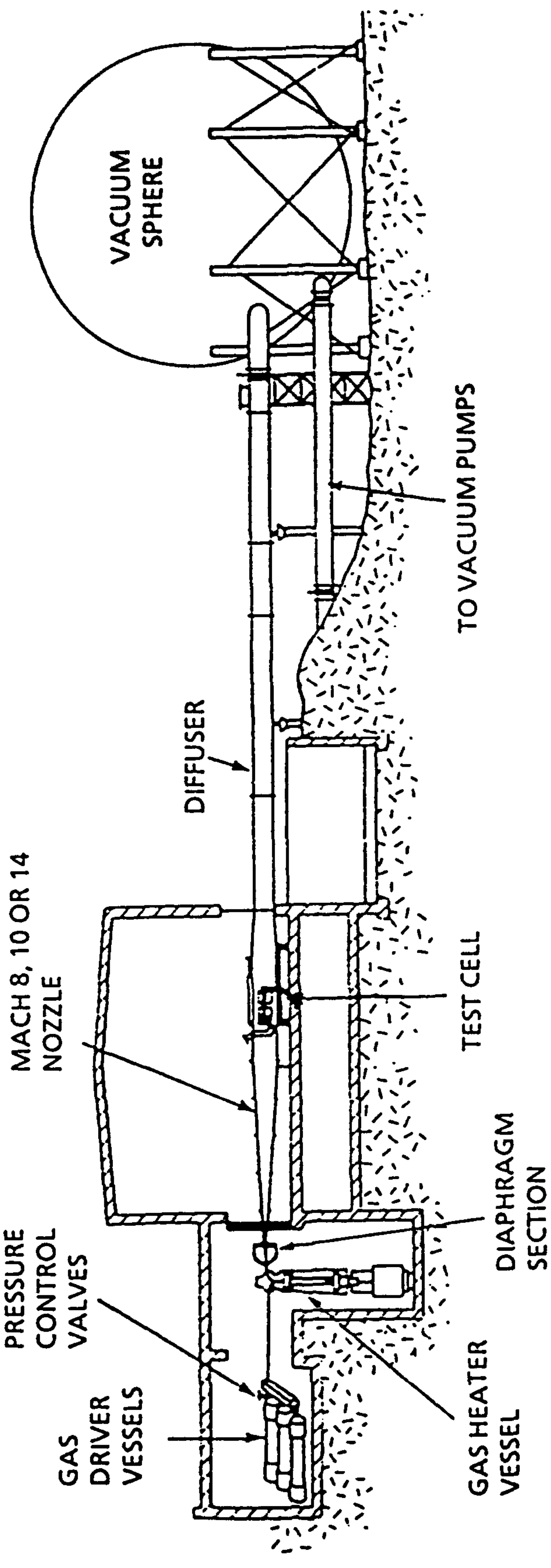

FIGURE 1. HYPERVELOCITY TUNNEL 9

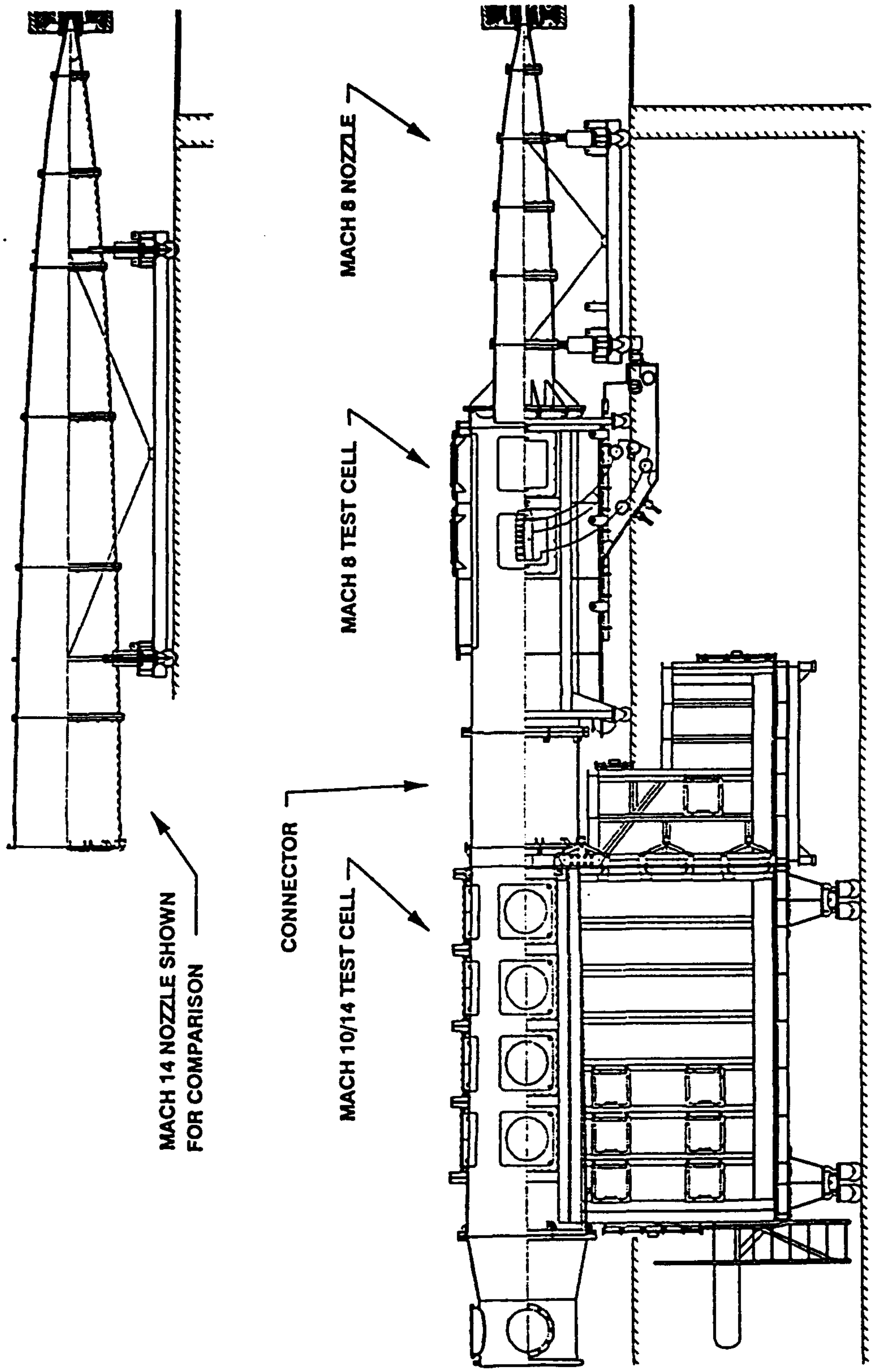

FIGURE 2. COMPARISON OF MACH 8 AND MACH 14 TUNNEL CONFIGURATIONS

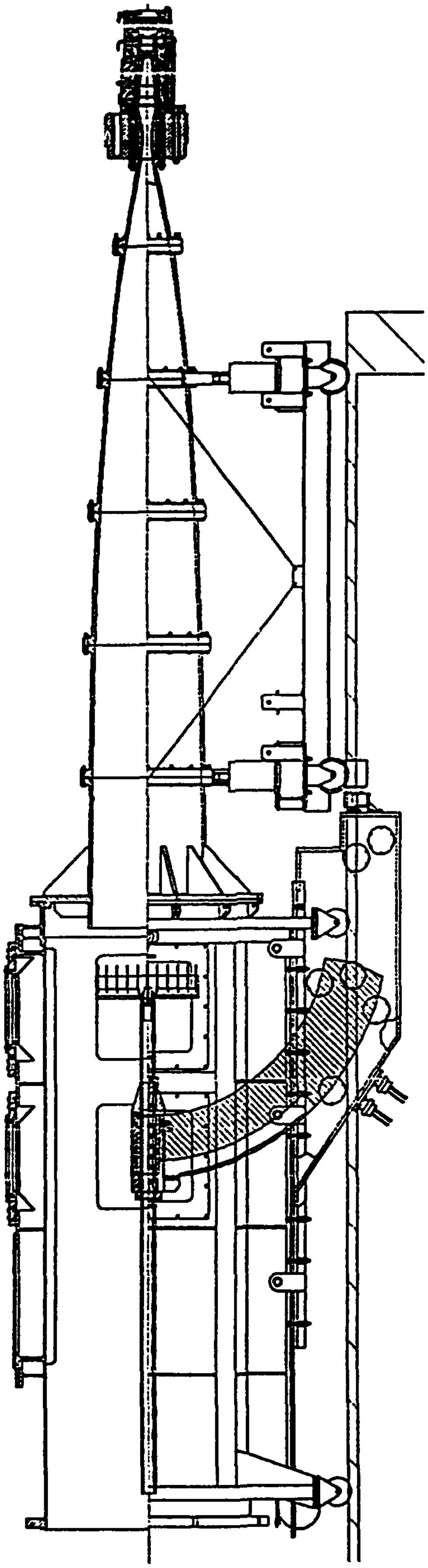

FIGURE 3. CALIBRATION PITOT RAKE INSTALLED IN MACH 8 TEST CELL

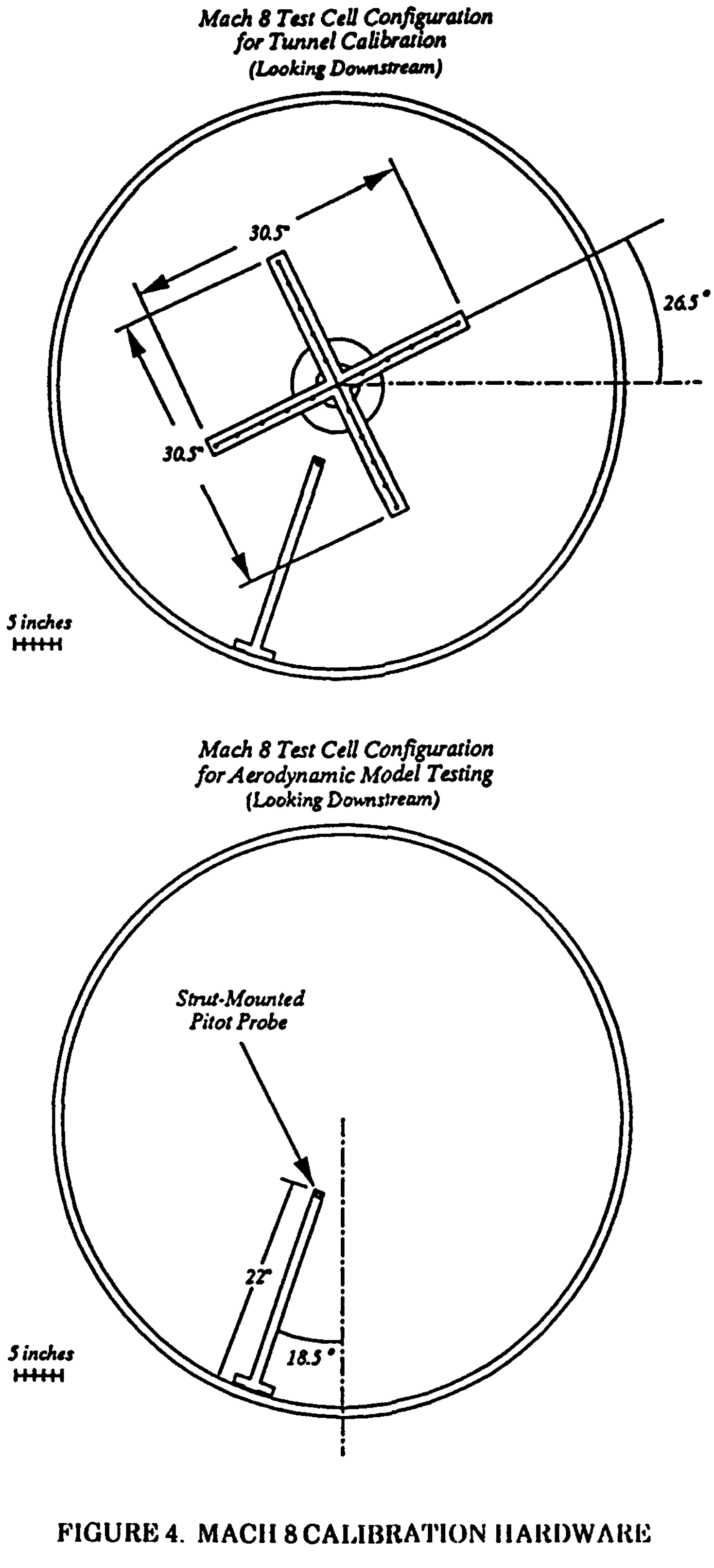

FIGURE 4. MACH 8 CALIBRATION HARDWARE

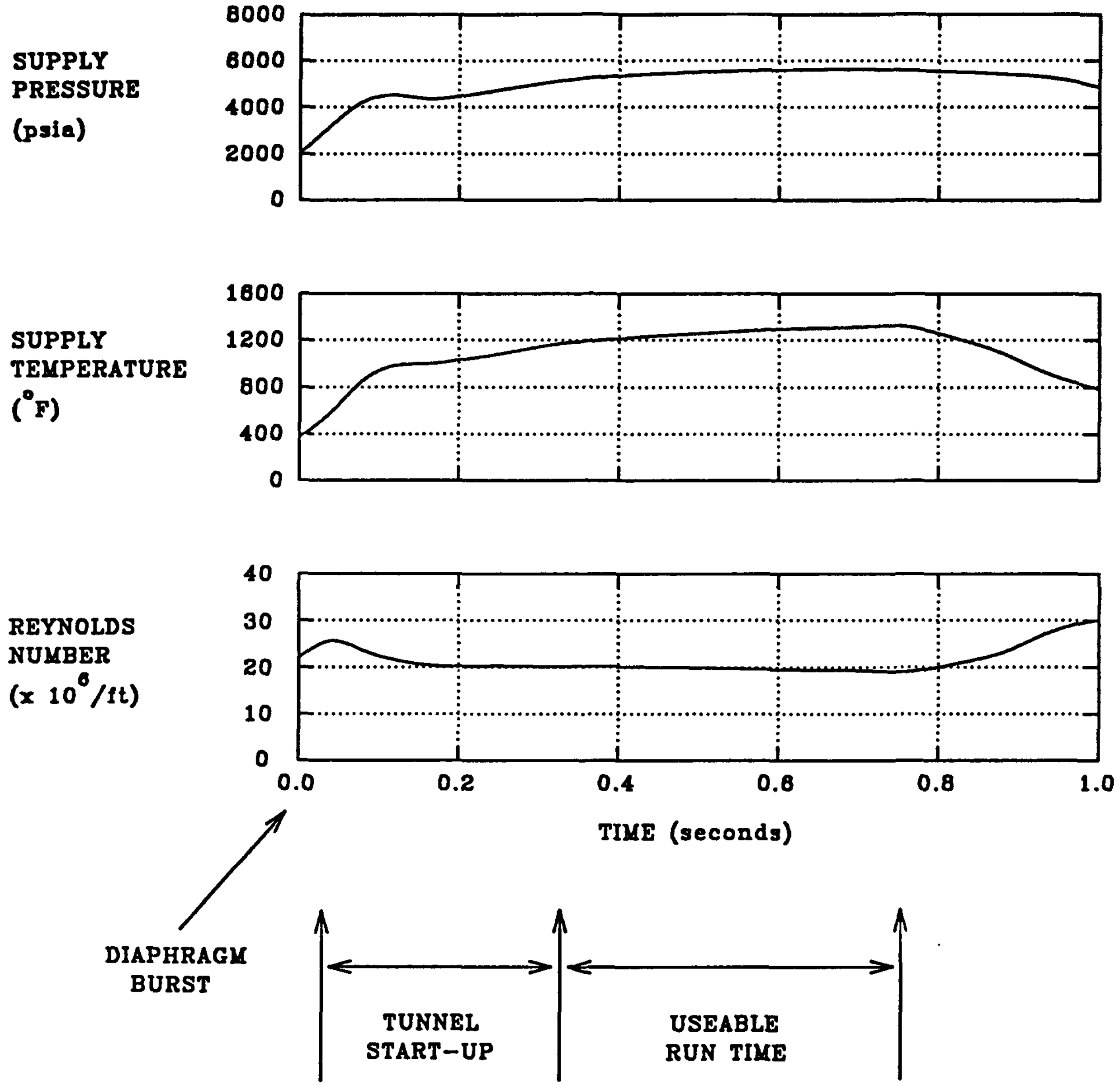

FIGURE 5. MACH 8 USABLE RUN TIME DEFINED BY SUPPLY CONDITIONS AND REYNOLDS NUMBER

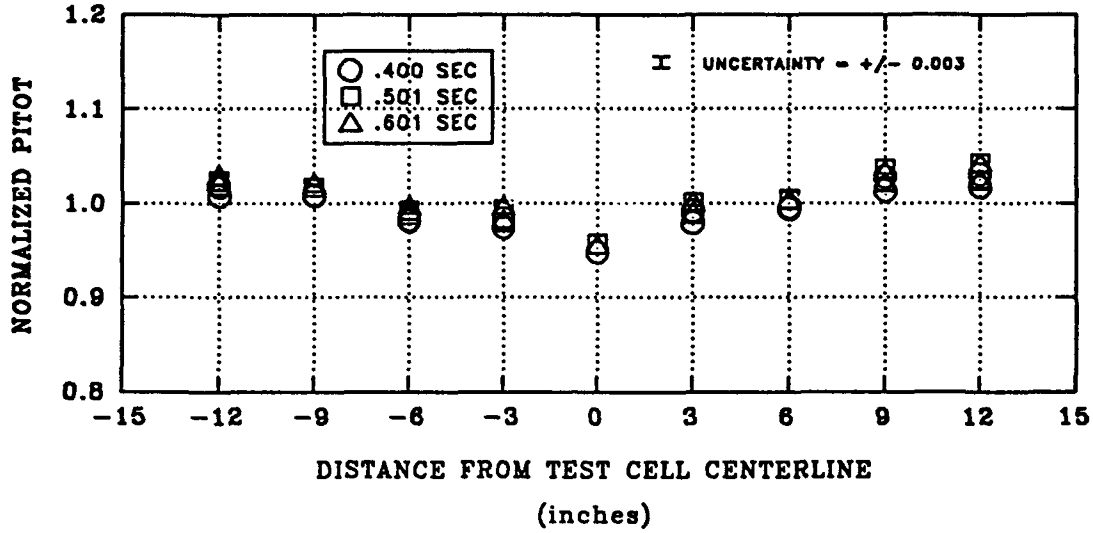

FIGURE 6. MACH 8 TEMPORAL UNIFORMITY

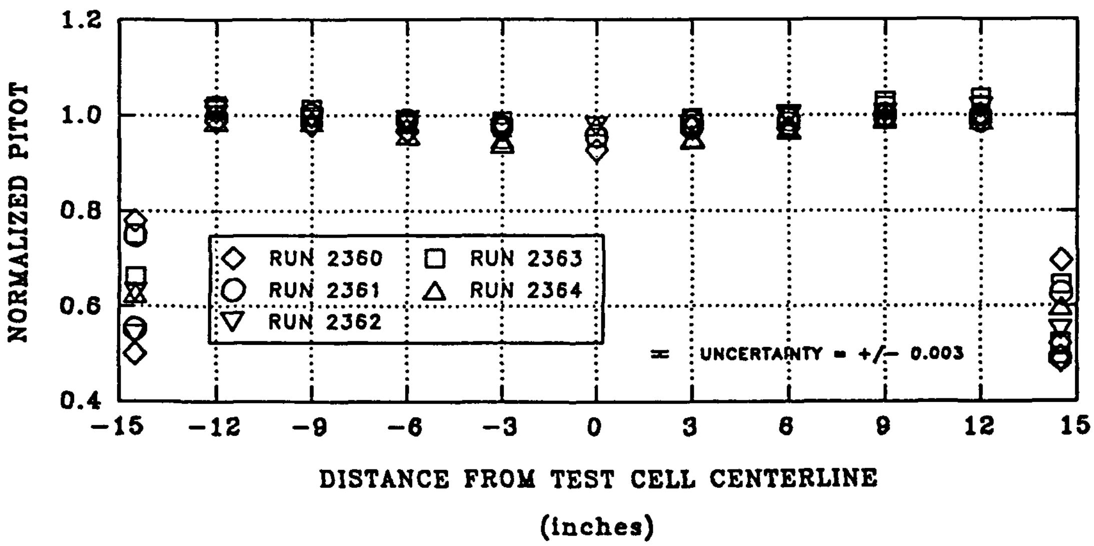

FIGURE 7. MACH 8 RADIAL INVISCID CORE SIZE 11 INCHES DOWNSTREAM OF THE NOZZLE EXIT

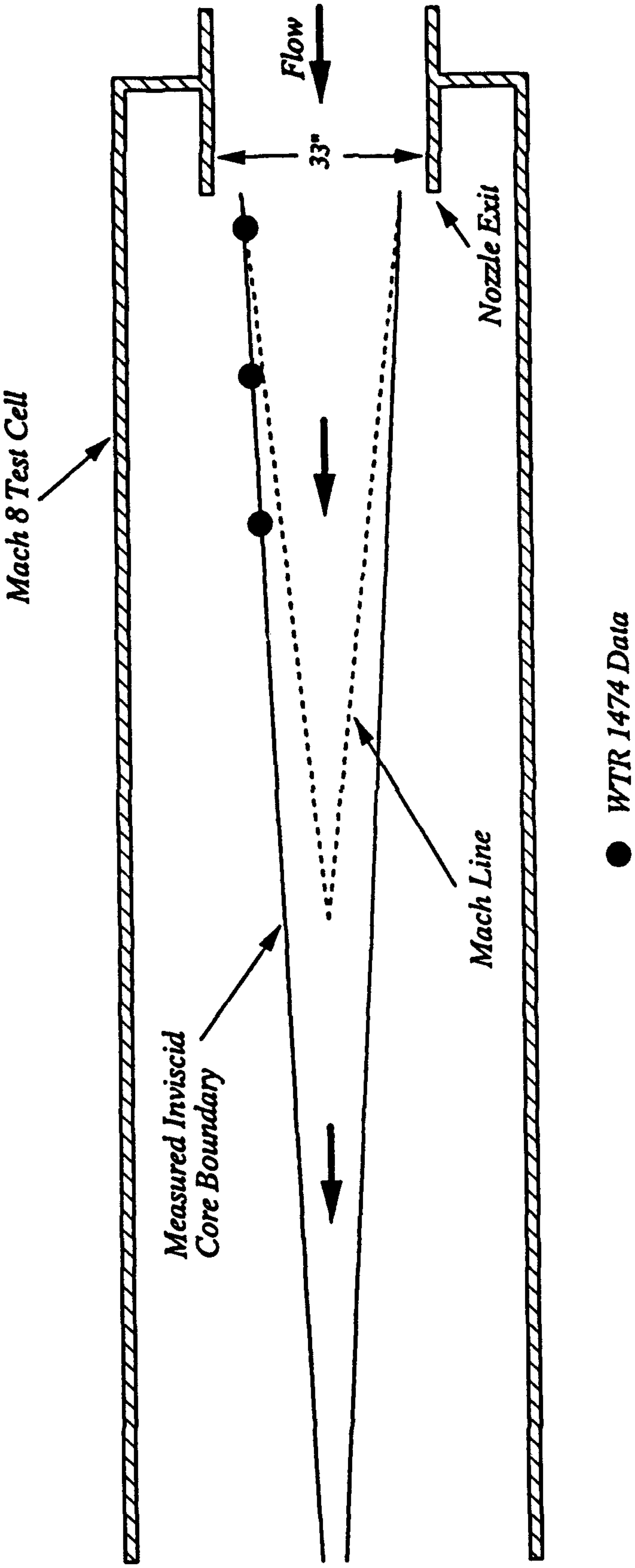

FIGURE 8. AXIAL VARIATION OF THE MACH 8 INVISCID CORE SIZE

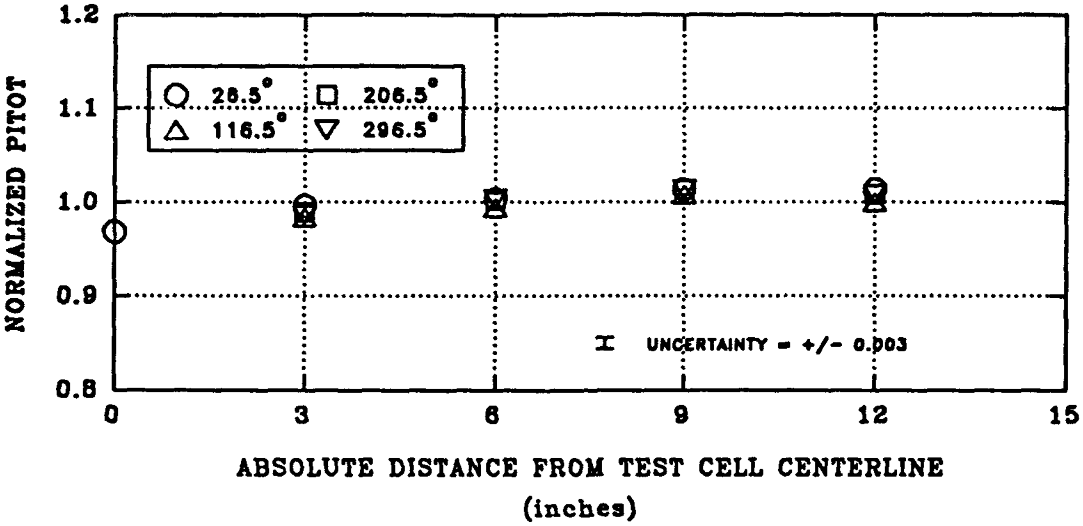

FIGURE 9. RADIAL SYMMETRY OF THE MACH 8 INVISCID CORE 11 INCHES DOWNSTREAM OF THE NOZZLE EXIT

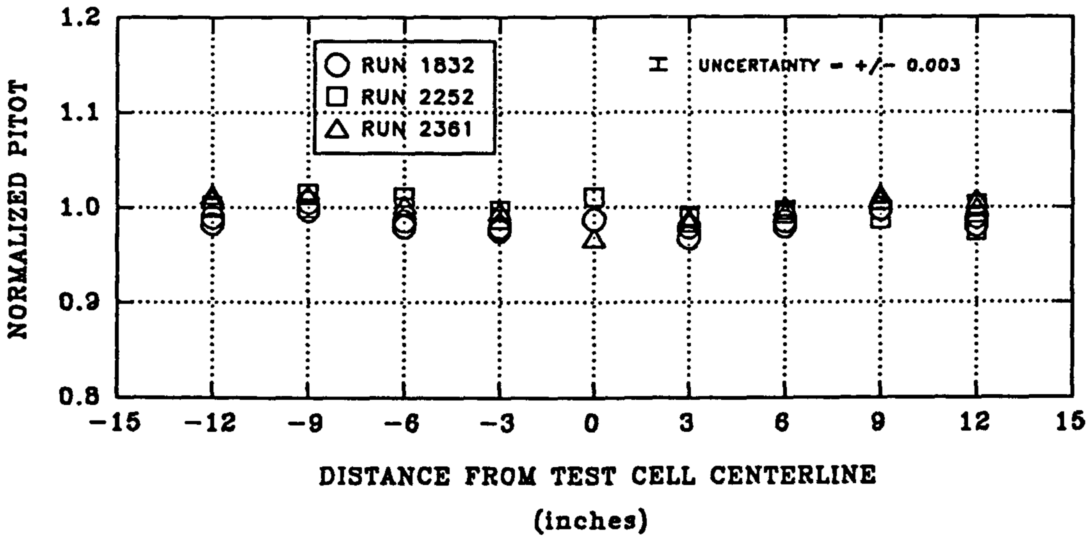

FIGURE 10. COMPARISON OF MACH 8 RUN REPEATABILITY

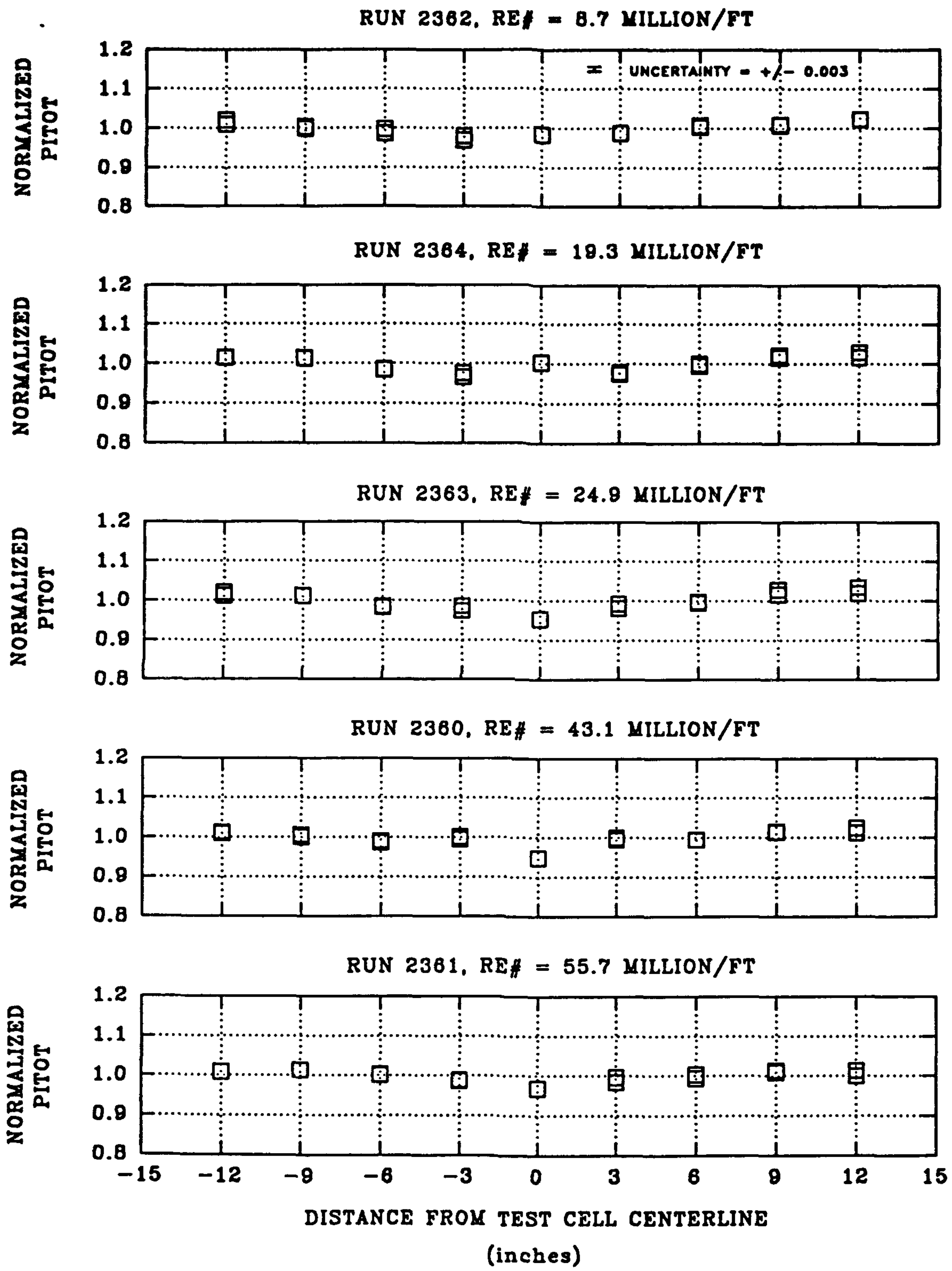

FIGURE 11. MACH 8 NORMALIZED PITOT PRESSURE PROFILES

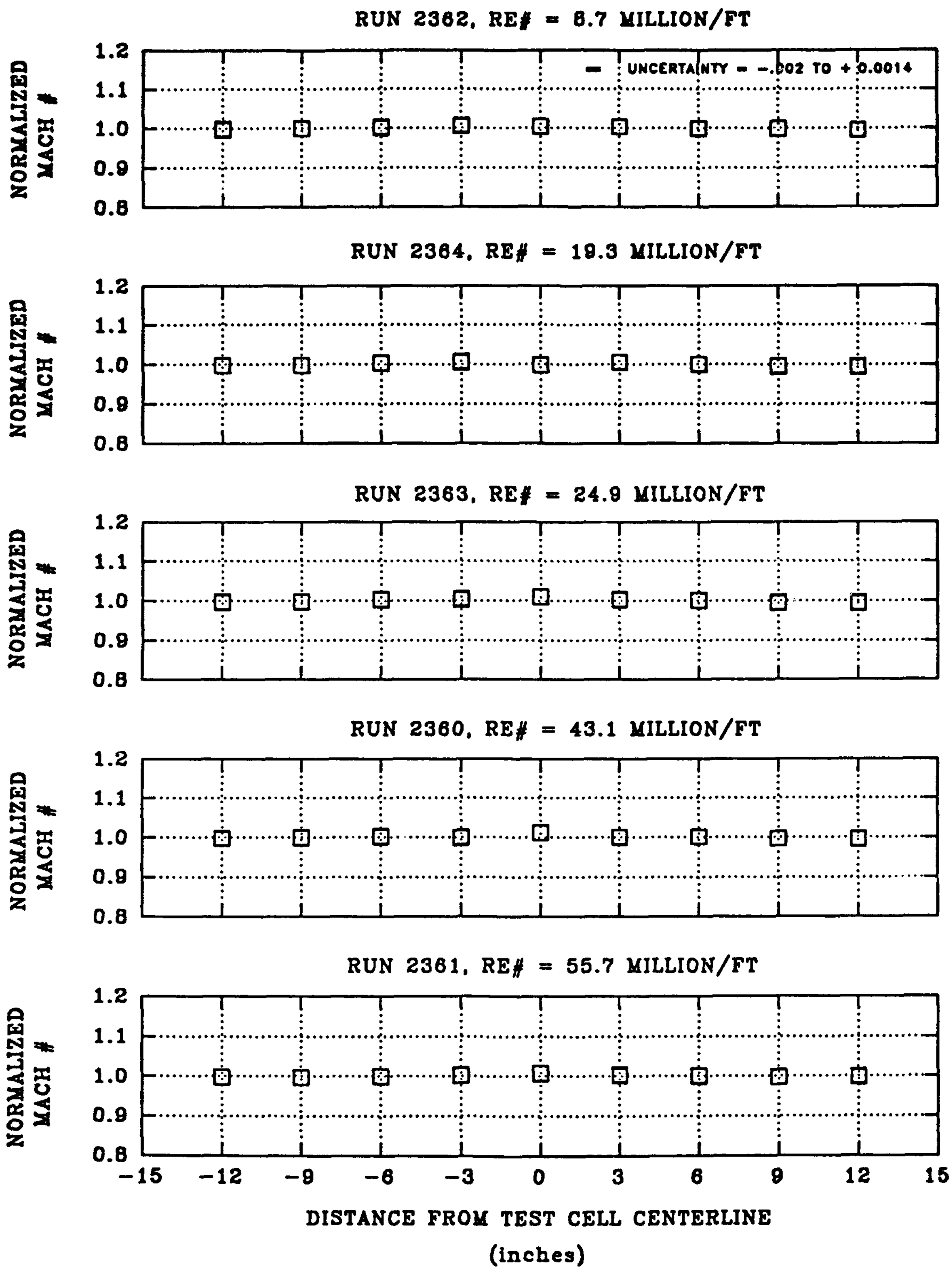

FIGURE 12. MACH 8 NORMALIZED MACH NUMBER PROFILES

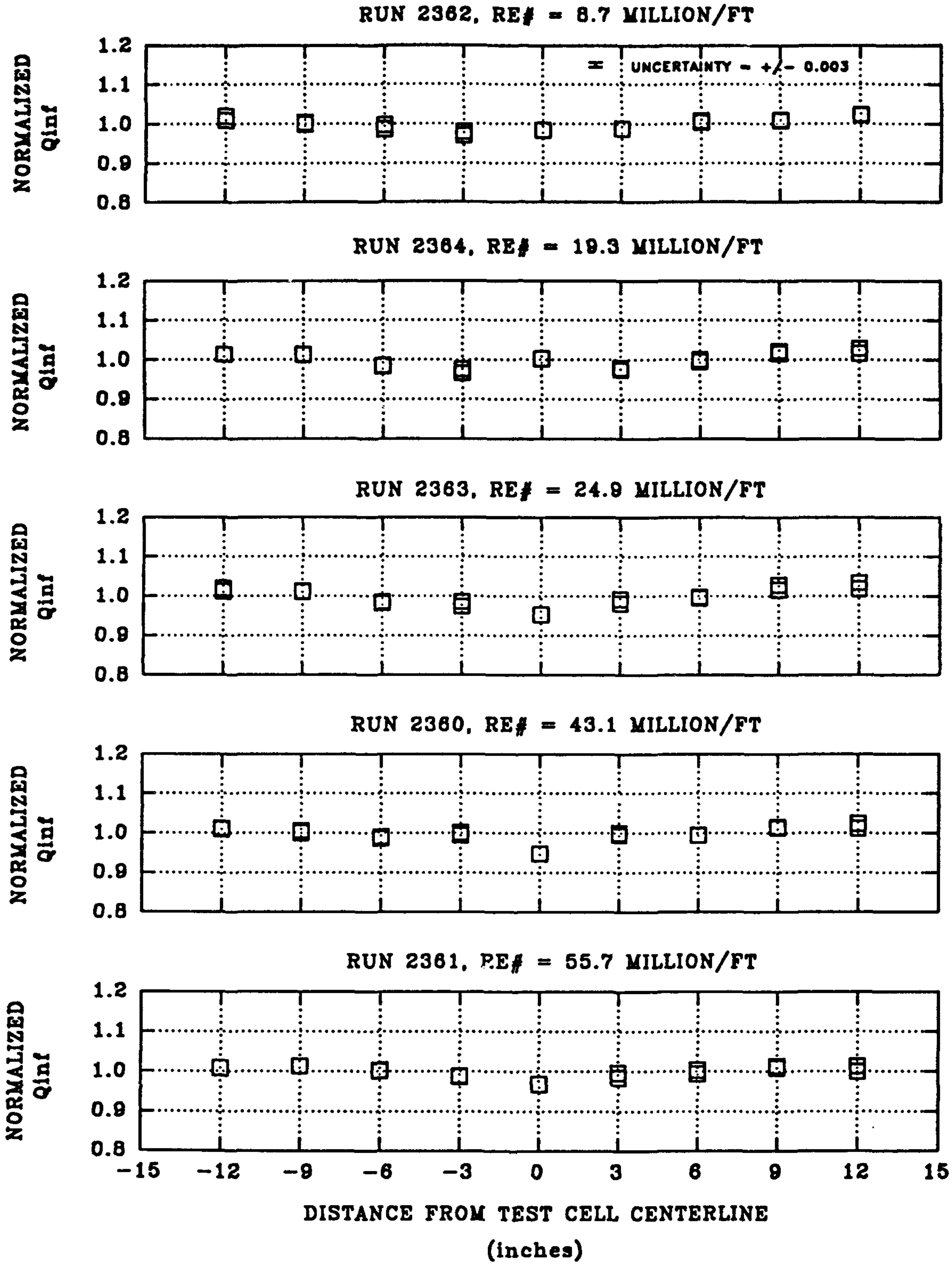

FIGURE 13. MACH 8 NORMALIZED DYNAMIC PRESSURE PROFILES

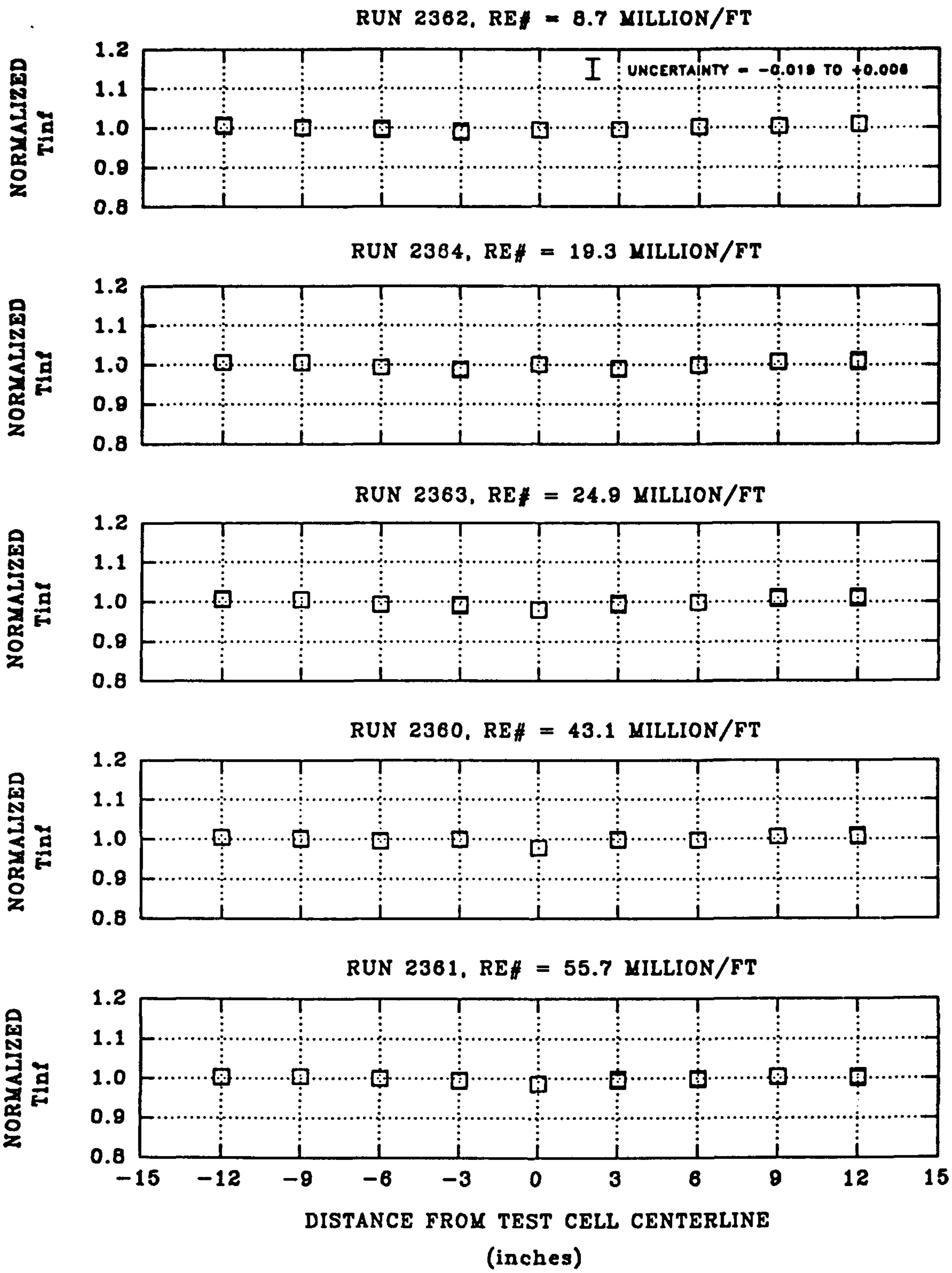

FIGURE 14. MACH 8 NORMALIZED TEMPERATURE PROFILES

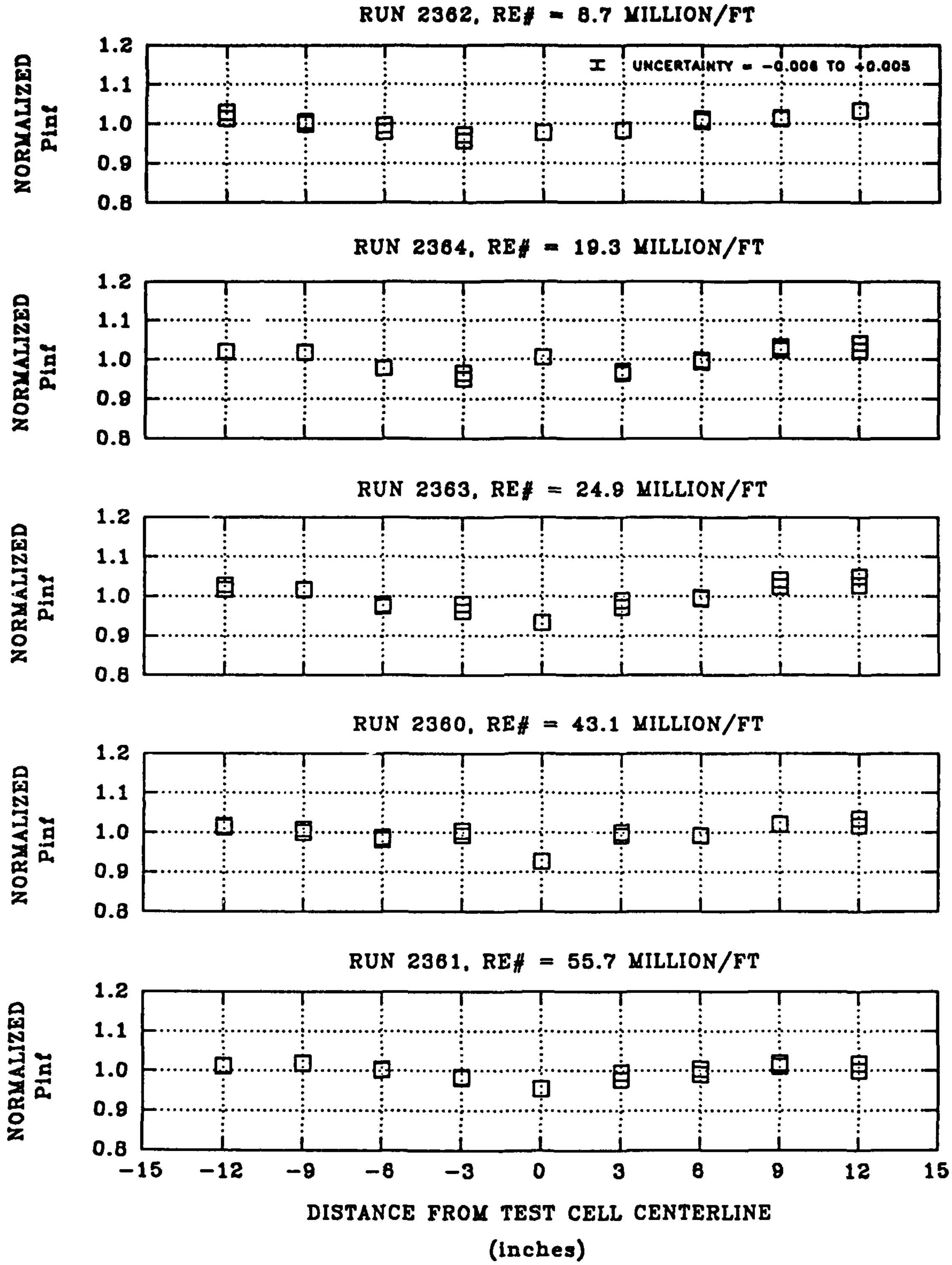

FIGURE 15. MACH 8 NORMALIZED PRESSURE PROFILES

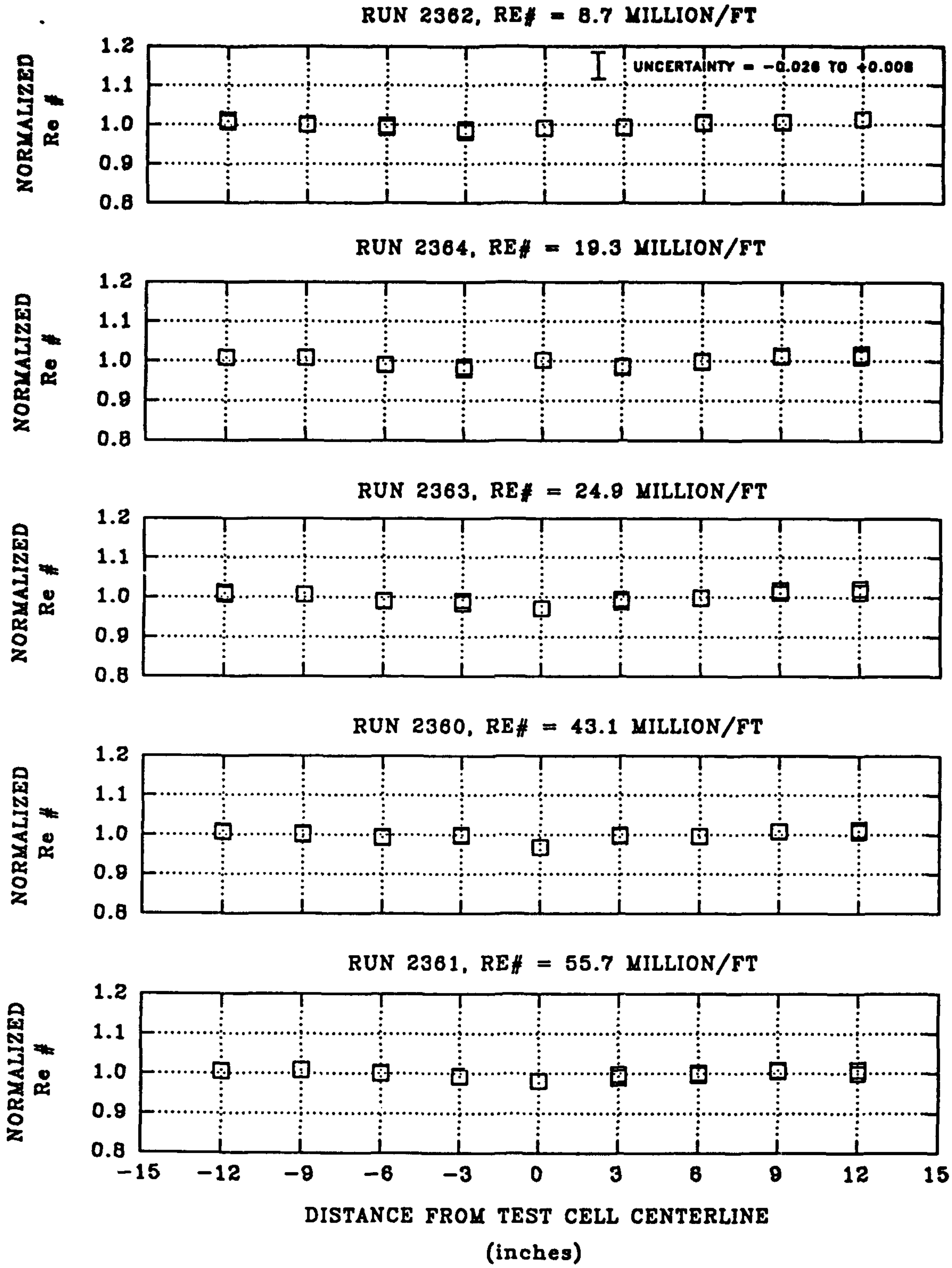

FIGURE 16. MACH 8 NORMALIZED REYNOLDS NUMBER PROFILES

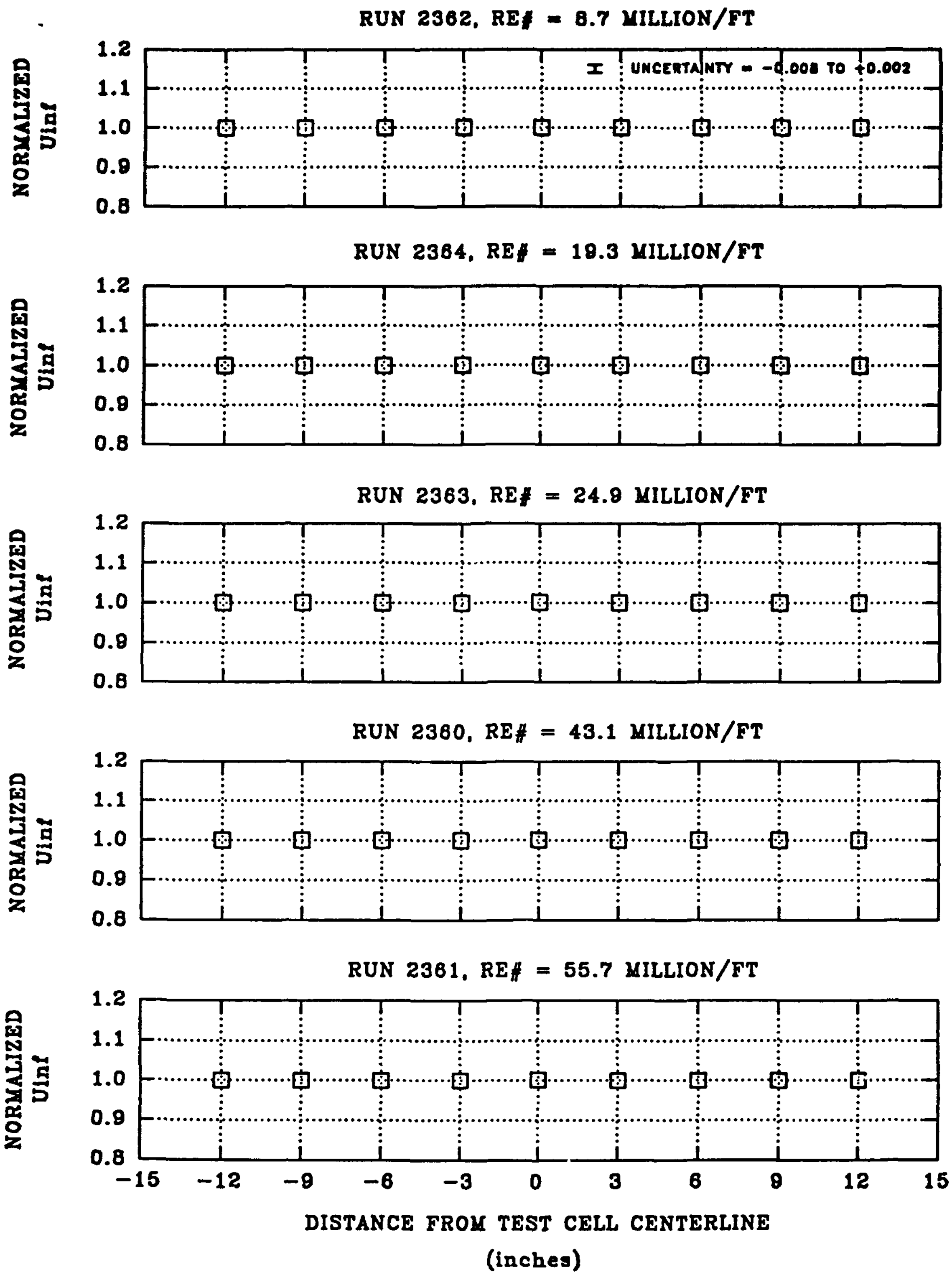

FIGURE 17. MACH 8 NORMALIZED VELOCITY PROFILES

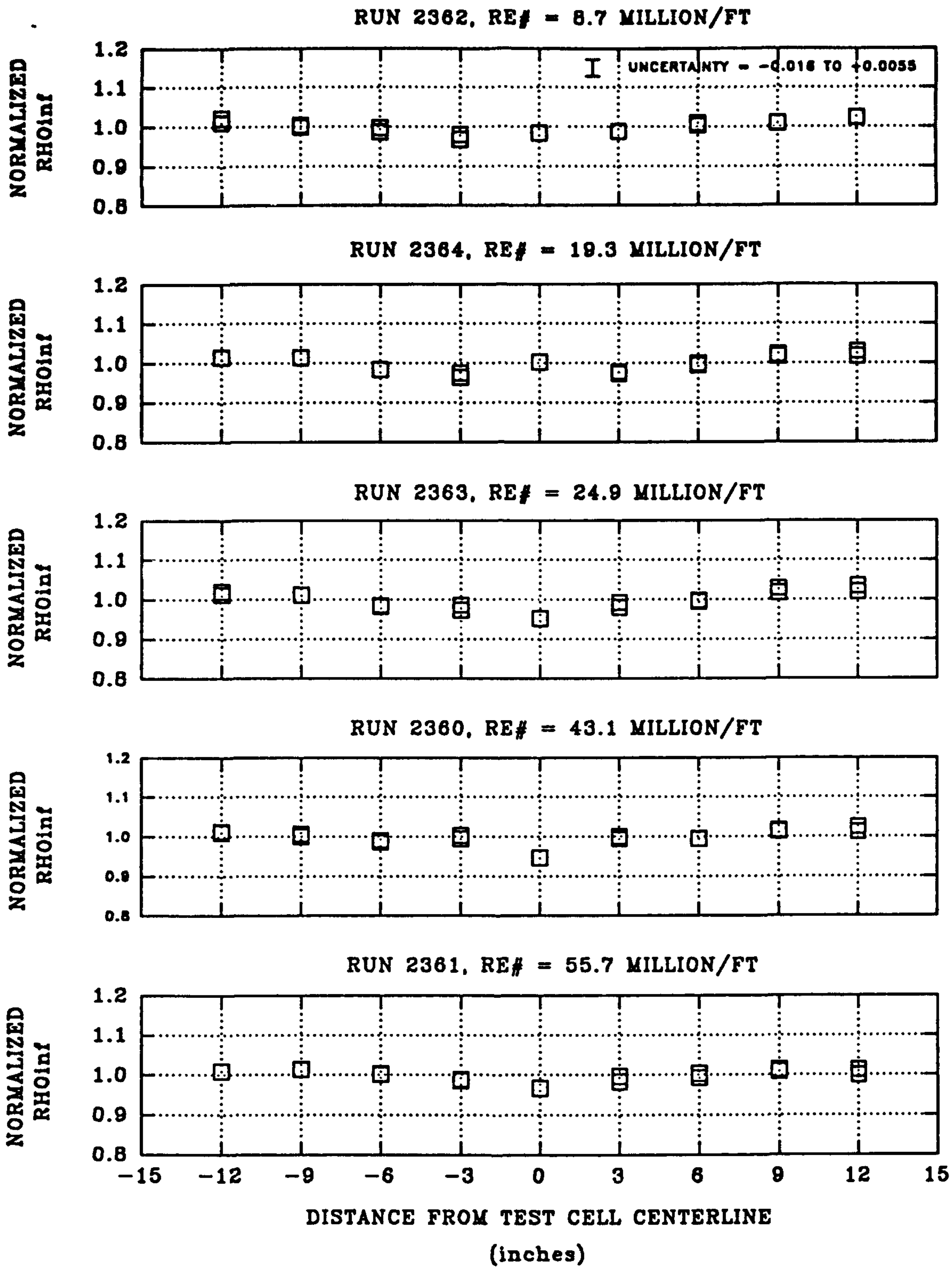

FIGURE 18. MACH 8 NORMALIZED DENSITY PROFILES

TABLE 1. CURRENT TUNNEL 9 CAPABILITIES

Contoured Nozzle	Supply Pressure Range (psia)	Nominal Supply Temperature (°F)	Reynolds Number Range (x 10^6/ft)	Run Time Range (s)
8	2,000 to 11,800	1,200	8.7 to 55.7	.20 to .75
10	500 to 14,000	1,350	0.86 to 21.9	.23 to 8
14	100 to 20,000	2,750	0.072 to 3.8	.7 to 15

TABLE 2. TUNNEL 9 MACH 8 SUPPLY/PITOT PRESSURE INSTRUMENTATION

Reynolds Number (x10^6/ft)	Supply Pressure Transducer (Range)	Pitot Pressure Transducer (Range)
8.7	Viatran Model 304 (0 - 10,000 psia)	Kulite model XT-140-200A (0 - 200 psia)
19.3	Viatran Model 304 (0 - 10,000 psia)	Kulite model XT-140-200A (0 - 200 psia)
24.9	Viatran Model 304 (0 - 10,000 psia)	Kulite model XT-140-200A (0 - 200 psia)
43.1	Viatran Model 1212BQ2AAA20 (0 - 20,000 psia)	Kulite model XT-140-200A (0 - 200 psia)
55.7	Viatran Model 1212BQ2AAA20 (0 - 20,000 psia)	Kulite model XT-140-200A (0 - 200 psia)

TABLE 3. TUNNEL 9 MEASURED AND DERIVED PARAMETER UNCERTAINTIES

Measured Property	Documented Uncertainty
P_o	±0.4%
T_o	-1.7 to +0.5%
Pitot	±0.3%
Resulting Uncertainties in Derived Properties	
Mach	-0.2 to +0.14%
Re#/L	-2.6 to +0.8%
p_∞	-0.6 to +0.5%
T_∞	-1.9 to +0.6%
q_∞	±0.3%
ρ_∞	-1.6 to +0.55%
U_∞	-0.8 to +0.2%

TABLE 4. MACH 8 NOMINAL TEST CELL AND SUPPLY CONDITIONS

Supply Pressure P_o (psia)	Supply Temperature T_o (°F)	Pitot Pressure PT (psia)	Dynamic Pressure q_∞ (psia)	Static Pressure p_∞ (psia)	Static Temperature T_∞ (°R)	Free Stream Density ρ_∞ (lb_m/ft^3)	Free Stream Velocity V_∞ (ft/sec)	Free Stream Reynolds # Re/L ($x10^6$/ft)	Free Stream Mach # M	Viscous Interaction Parameter $M/\sqrt{Re/L}$ ($ft^{1/2}$)	Useable Run Time (sec)
MACH 8											
1965	1048	24.89	13.44	.354	131.2	.00703	4208	8.7	7.37	.00250	.75
5474	1261	67.54	36.49	.921	148.2	.0162	4568	19.3	7.52	.00171	.45
6619	1200	81.97	44.29	1.10	141.5	.0203	4498	24.9	7.58	.00152	.4
10474	1105	126.59	68.42	1.60	128.2	.0325	4417	43.1	7.82	.00119	.2
11738	985	142.61	77.09	1.76	116.0	.0395	4253	55.7	7.92	.00106	.2

TABLE 5. TUNNEL 9 MACH 8 CALIBRATION DATA

Run #	Mach #	Re#/ft x 10^6	Axial Station (inches)	Supply Pressure (psia)	Supply Temperature (°F)	PTAVG (psia)	PTmean/ PTAVG	Deviation in Pressure ± %	Core Diameter (inches)
2360	7.82	43.1	11	10474	1105	126.59	0.977	+0.4% to -7.1%	24
2361	7.92	55.7	11	11738	985	142.61	0.975	-1.0% to -5.4%	24
2362	7.37	8.7	11	1965	1048	24.89	0.987	+1.0% to -4.2%	24
2363	7.58	24.9	11	6619	1200	81.97	0.997	+3.2% to -3.7%	24
2364	7.52	19.3	11	5474	1261	67.54	0.985	+1.3% to -4.9%	24

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APPENDIX A

FREE STREAM FLOW FIELD PARAMETERS FOR ALL NOMINAL TEST CONDITIONS

TUNNEL 9 FLOW UNIFORMITY CALIBRATION
WTR 1614, RUN 2362, STATION 11.0 inches

MACH = 7.37 PO = 1965. psia TO = 1048. degF PTAVG = 24.89 psia

NOMINAL FREESTREAM CONDITIONS

MACH	QINF psia	TINF degR	PINF psia	REINF 1/ft	UINF ft/sec	RHOINF lbm/ft3	VIP ft**1/2
7.37	13.443	131.2	3.54E-01	8.70E+06	4208.	7.03E-03	2.50E-03

PROFILES NORMALIZED TO NOMINAL

Probe #	Dist. from center (in)	PT	M	Q	T	P	RE	U	RHO	VIP
HORIZONTAL										
1	14.50	0.552	1.142	0.553	0.783	0.424	0.696	1.010	0.542	1.369
2	12.00	1.022	0.995	1.022	1.009	1.033	1.014	1.000	1.023	0.988
3	9.00	1.010	0.998	1.010	1.004	1.015	1.006	1.000	1.010	0.995
4	6.00	1.003	0.999	1.003	1.001	1.005	1.002	1.000	1.003	0.998
5	3.00	0.988	1.003	0.988	0.995	0.983	0.993	1.000	0.988	1.006
6	0.00	0.984	1.004	0.984	0.993	0.977	0.990	1.000	0.984	1.008
7	-3.00	0.980	1.005	0.980	0.992	0.972	0.988	1.000	0.980	1.011
8	-6.00	0.986	1.003	0.986	0.994	0.980	0.992	1.000	0.986	1.007
9	-9.00	1.004	0.999	1.004	1.002	1.006	1.002	1.000	1.004	0.998
10	-12.00	1.020	0.996	1.020	1.008	1.029	1.012	1.000	1.021	0.989
11	-14.50	0.540	1.147	0.541	0.776	0.411	0.687	1.010	0.530	1.384
VERTICAL										
12	14.50	0.482	1.176	0.483	0.740	0.349	0.640	1.012	0.471	1.470
13	12.00	1.023	0.995	1.023	1.009	1.033	1.014	1.000	1.024	0.988
14	9.00	1.008	0.998	1.008	1.003	1.012	1.005	1.000	1.009	0.996
15	6.00	1.008	0.998	1.008	1.003	1.012	1.005	1.000	1.009	0.996
16	3.00	0.988	1.003	0.988	0.995	0.982	0.992	1.000	0.987	1.007
6	0.00	0.984	1.004	0.984	0.993	0.977	0.990	1.000	0.984	1.008
17	-3.00	0.969	1.007	0.970	0.987	0.956	0.981	1.001	0.968	1.017
18	-6.00	0.997	1.001	0.997	0.999	0.996	0.998	1.000	0.997	1.001
19	-9.00	0.998	1.000	0.998	0.999	0.998	0.999	1.000	0.998	1.001
20	-12.00	1.009	0.998	1.009	1.004	1.013	1.006	1.000	1.010	0.995
21	-14.50	0.634	1.107	0.634	0.828	0.517	0.757	1.008	0.624	1.273

TUNNEL 9 FLOW UNIFORMITY CALIBRATION
WTR 1614, RUN 2364, STATION 11.0 inches

MACH = 7.52 PO = 5474. psia TO = 1261. degF PTAVG = 67.54 psia

NOMINAL FREESTREAM CONDITIONS

MACH	QINF psia	TINF degR	PINF psia	REINF 1/ft	UINF ft/sec	RHOINF lbm/ft3	VIP ft**1/2
7.52	36.488	148.2	9.21E-01	1.93E+07	4568.	1.62E-02	1.71E-03

PROFILES NORMALIZED TO NOMINAL

Probe #	Dist. from center (in)	PT	M	Q	T	P	RE	U	RHO	VIP
HORIZONTAL										
1	14.50	0.615	1.114	0.615	0.818	0.496	0.743	1.008	0.606	1.293
2	12.00	1.029	0.994	1.029	1.012	1.042	1.018	0.999	1.030	0.985
3	9.00	1.022	0.995	1.022	1.009	1.032	1.013	1.000	1.023	0.989
4	6.00	0.995	1.001	0.995	0.998	0.993	0.997	1.000	0.995	1.003
5	3.00	0.979	1.005	0.979	0.991	0.969	0.987	1.000	0.978	1.012
6	0.00	1.003	0.999	1.003	1.001	1.005	1.002	1.000	1.003	0.998
7	-3.00	0.976	1.005	0.976	0.990	0.965	0.985	1.000	0.975	1.013
8	-6.00	0.984	1.004	0.984	0.994	0.978	0.990	1.000	0.984	1.008
9	-9.00	1.012	0.997	1.012	1.005	1.018	1.008	1.000	1.013	0.993
10	-12.00	1.014	0.997	1.014	1.006	1.020	1.008	1.000	1.014	0.993
11	-14.50	0.644	1.103	0.644	0.834	0.530	0.764	1.007	0.635	1.262
VERTICAL										
12	14.50	0.511	1.161	0.511	0.758	0.380	0.663	1.011	0.501	1.425
13	12.00	1.016	0.996	1.016	1.007	1.023	1.010	1.000	1.017	0.992
14	9.00	1.016	0.996	1.016	1.007	1.024	1.010	1.000	1.017	0.991
15	6.00	1.000	1.000	1.000	1.000	0.999	1.000	1.000	1.000	1.000
16	3.00	0.974	1.006	0.974	0.989	0.963	0.984	1.000	0.973	1.014
6	0.00	1.003	0.999	1.003	1.001	1.005	1.002	1.000	1.003	0.998
17	-3.00	0.966	1.008	0.966	0.986	0.950	0.979	1.001	0.964	1.019
18	-6.00	0.985	1.003	0.985	0.994	0.978	0.991	1.000	0.984	1.008
19	-9.00	1.013	0.997	1.013	1.005	1.019	1.008	1.000	1.014	0.993
20	-12.00	1.015	0.997	1.014	1.006	1.021	1.009	1.000	1.015	0.992
21	-14.50	0.718	1.077	0.719	0.872	0.620	0.817	1.006	0.711	1.191

TUNNEL 9 FLOW UNIFORMITY CALIBRATION
WTR 1614, RUN 2363, STATION 11.0 inches

MACH = 7.58 P0 = 6619. psia T0 = 1200. degF PTAVG = 81.97 psia

NOMINAL FREESTREAM CONDITIONS

MACH	QINF psia	TINF degR	PINF psia	REINF 1/ft	UINF ft/sec	RHOINF lbm/ft3	VIP ft**1/2
7.58	44.288	141.5	1.10E+00	2.49E+07	4498.	2.03E-02	1.52E-03

PROFILES NORMALIZED TO NOMINAL

Probe #	Dist. from center (in)	PT	M	Q	T	P	RE	U	RHO	VIP
HORIZONTAL										
1	14.50	0.645	1.102	0.646	0.835	0.531	0.765	1.007	0.637	1.260
2	12.00	1.034	0.993	1.034	1.014	1.050	1.021	0.999	1.035	0.982
3	9.00	1.028	0.994	1.028	1.012	1.041	1.017	0.999	1.029	0.985
4	6.00	0.995	1.001	0.995	0.998	0.993	0.997	1.000	0.995	1.002
5	3.00	0.992	1.002	0.992	0.997	0.989	0.995	1.000	0.992	1.004
6	0.00	0.953	1.011	0.953	0.980	0.933	0.971	1.001	0.952	1.026
7	-3.00	0.986	1.003	0.986	0.994	0.980	0.991	1.000	0.986	1.007
8	-6.00	0.986	1.003	0.986	0.994	0.980	0.991	1.000	0.986	1.007
9	-9.00	1.012	0.997	1.012	1.005	1.018	1.007	1.000	1.012	0.994
10	-12.00	1.020	0.996	1.020	1.008	1.029	1.012	1.000	1.020	0.990
11	-14.50	0.663	1.096	0.663	0.844	0.552	0.778	1.007	0.654	1.243
VERTICAL										
12	14.50	0.521	1.155	0.522	0.765	0.391	0.672	1.010	0.512	1.409
13	12.00	1.019	0.996	1.019	1.008	1.028	1.012	1.000	1.020	0.990
14	9.00	1.016	0.996	1.016	1.007	1.024	1.010	1.000	1.017	0.991
15	6.00	0.998	1.000	0.998	0.999	0.997	0.999	1.000	0.998	1.001
16	3.00	0.981	1.004	0.981	0.992	0.972	0.988	1.000	0.980	1.010
6	0.00	0.953	1.011	0.953	0.980	0.933	0.971	1.001	0.952	1.026
17	-3.00	0.974	1.006	0.974	0.989	0.962	0.984	1.000	0.973	1.014
18	-6.00	0.982	1.004	0.982	0.993	0.974	0.989	1.000	0.982	1.010
19	-9.00	1.011	0.998	1.011	1.005	1.016	1.007	1.000	1.011	0.994
20	-12.00	1.012	0.997	1.012	1.005	1.017	1.007	1.000	1.012	0.994
21	-14.50	0.752	1.066	0.752	0.889	0.662	0.840	1.005	0.745	1.163

TUNNEL 9 FLOW UNIFORMITY CALIBRATION
WTR 1614, RUN 2360, STATION 11.0 inches

MACH = 7.82 P0 = 10474. psia T0 = 1105. degF PTAVG = 126.59 psia

NOMINAL FREESTREAM CONDITIONS

MACH	QINF psia	TINF degR	PINF psia	REINF 1/ft	UINF ft/sec	RHOINF lbm/ft3	VIP ft**1/2
7.82	68.422	128.2	1.60E+00	4.31E+07	4417.	3.25E-02	1.19E-03

PROFILES NORMALIZED TO NOMINAL

Probe #	Dist. from center (in)	PT	M	Q	T	P	RE	U	RHO	VIP
HORIZONTAL										
1	14.50	0.712	1.078	0.713	0.870	0.613	0.813	1.005	0.705	1.196
2	12.00	1.024	0.995	1.024	1.010	1.035	1.014	1.000	1.025	0.988
3	9.00	1.015	0.997	1.015	1.006	1.022	1.009	1.000	1.016	0.992
4	6.00	0.994	1.001	0.994	0.997	0.991	0.996	1.000	0.994	1.003
5	3.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
6	0.00	0.948	1.012	0.948	0.978	0.926	0.968	1.001	0.946	1.029
7	-3.00	1.002	0.999	1.002	1.001	1.004	1.001	1.000	1.003	0.999
8	-6.00	0.987	1.003	0.987	0.994	0.981	0.992	1.000	0.986	1.007
9	-9.00	1.006	0.999	1.006	1.003	1.009	1.004	1.000	1.007	0.997
10	-12.00	1.013	0.997	1.013	1.005	1.018	1.008	1.000	1.013	0.993
11	-14.50	0.512	1.158	0.513	0.760	0.382	0.665	1.010	0.503	1.421
VERTICAL										
12	14.50	0.531	1.149	0.532	0.771	0.403	0.680	1.009	0.522	1.394
13	12.00	1.012	0.997	1.012	1.005	1.017	1.007	1.000	1.012	0.994
14	9.00	1.014	0.997	1.013	1.006	1.020	1.008	1.000	1.014	0.993
15	6.00	0.995	1.001	0.995	0.998	0.993	0.997	1.000	0.995	1.002
16	3.00	0.994	1.001	0.994	0.997	0.991	0.996	1.000	0.994	1.003
6	0.00	0.948	1.012	0.948	0.978	0.926	0.968	1.001	0.946	1.029
17	-3.00	0.995	1.001	0.995	0.998	0.993	0.997	1.000	0.995	1.002
18	-6.00	0.991	1.002	0.991	0.996	0.988	0.995	1.000	0.991	1.005
19	-9.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
20	-12.00	1.010	0.998	1.010	1.004	1.014	1.006	1.000	1.010	0.995
21	-14.50	0.798	1.051	0.798	0.911	0.722	0.871	1.004	0.793	1.126

TUNNEL 9 FLOW UNIFORMITY CALIBRATION
WTR 1614, RUN 2361, STATION 11.0 inches

MACH = 7.92 P0 = 11738. psia T0 = 985. degF PTAVG = 142.61 psia

NOMINAL FREESTREAM CONDITIONS

MACH	QINF psia	TINF degR	PINF psia	REINF 1/ft	UINF ft/sec	RHOINF lbm/ft3	VIP ft**1/2
7.92	77.091	116.0	1.76E+00	5.57E+07	4253.	3.95E-02	1.06E-03

PROFILES NORMALIZED TO NOMINAL

Probe #	Dist. from center (in)	PT	M	Q	T	P	RE	U	RHO	VIP
HORIZONTAL										
1	14.50	0.635	1.105	0.636	0.830	0.520	0.758	1.007	0.627	1.269
2	12.00	1.013	0.997	1.013	1.005	1.018	1.008	1.000	1.013	0.993
3	9.00	1.013	0.997	1.013	1.005	1.019	1.008	1.000	1.014	0.993
4	6.00	1.003	0.999	1.003	1.001	1.004	1.002	1.000	1.003	0.999
5	3.00	0.996	1.001	0.996	0.999	0.995	0.998	1.000	0.996	1.002
6	0.00	0.968	1.007	0.968	0.987	0.955	0.981	1.001	0.967	1.017
7	-3.00	0.989	1.002	0.989	0.996	0.985	0.994	1.000	0.989	1.006
8	-6.00	1.001	1.000	1.001	1.000	1.001	1.000	1.000	1.001	1.000
9	-9.00	1.013	0.997	1.013	1.005	1.019	1.008	1.000	1.014	0.993
10	-12.00	1.008	0.998	1.008	1.003	1.011	1.005	1.000	1.008	0.996
11	-14.50	0.560	1.136	0.560	0.788	0.434	0.702	1.008	0.551	1.356
VERTICAL										
12	14.50	0.495	1.167	0.496	0.750	0.365	0.651	1.010	0.486	1.445
13	12.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
14	9.00	1.008	0.998	1.008	1.003	1.011	1.005	1.000	1.008	0.996
15	6.00	0.994	1.001	0.994	0.997	0.991	0.996	1.000	0.993	1.003
16	3.00	0.984	1.004	0.984	0.993	0.977	0.990	1.000	0.983	1.009
6	0.00	0.968	1.007	0.968	0.987	0.955	0.981	1.001	0.967	1.017
17	-3.00	0.987	1.003	0.987	0.994	0.981	0.992	1.000	0.986	1.007
18	-6.00	1.003	0.999	1.003	1.001	1.004	1.002	1.000	1.003	0.999
19	-9.00	1.013	0.997	1.013	1.005	1.018	1.008	1.000	1.013	0.993
20	-12.00	1.009	0.998	1.009	1.004	1.013	1.006	1.000	1.009	0.995
21	-14.50	0.759	1.063	0.760	0.893	0.673	0.845	1.004	0.753	1.156

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13. ABSTRACT *(Maximum 200 words)*

This report documents the Mach 8 Calibration test program (WTR 1614) performed in the Navy's Hypervelocity Wind Tunnel (Tunnel 9). This was an in-house calibration test effort. Free stream flow field measurements were obtained for the Mach 8 nozzle, covering a wide range of Reynolds numbers. The calibration included running very low Reynolds numbers, not previously calibrated at Mach 8, as well as running at the current maximum supply conditions for Mach 8. The test period was 18 to 23 December 1992, with a total of five runs. Results from this test entry were combined with previous Mach 8 calibration data in the final analysis. Previous calibration data were taken when Mach 8 was originally brought on-line in December of 1988. The maximum supply conditions were lower during the original calibration than are currently available. However, data from this most recent calibration reveal that high quality uniform flow still exists and that deviations in core flow field parameters are comparable with other Tunnel 9 calibration data taken to date.

14. SUBJECT TERMS Calibration Mach 8 NSWC Tunnel 9	Wind Tunnel Hypersonics	15. NUMBER OF PAGES 45 16. PRICE CODE

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